Geometric Structures in Hadronic Cores of Extensive Air Showers Observed by KASCADE

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The geometric distribution of high-energy hadrons ≥ 100 GeV in shower cores measured with the KASCADE calorimeter is analyzed. The data are checked for sensitivity to hadronic interaction features and indications of new physics as discussed in the literature. The angular correlation of the most energetic hadrons and in particular the fraction of events with hadrons being aligned are quantified by means of the commonly used parameter λ_4. The analysis shows that the observed λ_4 distribution is compatible with that predicted by simulations and is not linked to an angular correlation from hadronic jet production at high energy. Another parameter, $d_4^{\max}$, describing distances between hadrons measured in the detector, is found to be sensitive both to the transverse momenta in secondary hadron production and the primary particle type. Transverse momenta in high-energy hadron interactions differing by a factor two or more from what is assumed in the standard simulations are disfavoured by the measured $d_4^{\max}$ distribution.

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I. INTRODUCTION

High-energy hadrons in extensive air showers offer a unique possibility to study interaction features well beyond the kinematic and energy region of earthbound accelerators. In particular, structures in hadronic shower cores might reflect properties of the particle production at an initial stage of the shower development. For example, the EAS-TOP Collaboration investigated multicore events recorded in the calorimeter and studied the cross-section of large p_t jet production in proton-air collisions [1]. In other studies, data taken by the KASCADE scintillator array and hadron calorimeter [2, 3] were used to investigate different aspects of hadronic interaction models. The correlation of the hadronic to the muonic and electromagnetic shower components [4, 5], as well as features of the particle production in the very forward region of nucleon-air collisions [6] were measured and compared to model predictions.

Geometric structures in hadronic shower cores at observation level are particularly interesting, as one expects QCD jet production to lead to secondary hadrons being naturally aligned to form line shape patterns [7]. Similar alignment structures might result from exotic hadron production processes [8]. Therefore, it is not surprising that the observation of aligned structures in a number of emulsion chamber experiments has initiated considerable experimental and theoretical efforts over the last two decades [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26].

Aligned event structures were, for instance, reported by the PAMIR experiment [9, 10]. An excess of events with substructure alignment above background fluctuations was found in the data for primary energies above an energy threshold of $8-10$ PeV (see e.g. [10, 11, 12, 13, 14, 15] and references therein). The most energetic event of $\simeq 10$ PeV that was measured in an emulsion experiment during flights with the Concorde airplane also shows alignment [16]. Furthermore, alignment was found in another individual high-energy event, estimated to have an energy >10 PeV, that was detected by a balloon borne emulsion chamber [17].

The experimental evidence of the existence of an alignment phenomenon, i.e. events with substructures being located in a line occurring more frequently than expected, is debated controversially, including the possibility of the excess being due to statistical fluctuations (see e.g. [16]).

At lower energy, no excess of aligned structures in air

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showers or direct experiments was observed. At energies of a few PeV the fraction of elongated events measured by PAMIR was found to agree with the expectations from background fluctuations. The fraction of elongated events of similar energy recorded by the Kanbala air shower experiment [18] gave also no indication of a significant excess over the simulated background. Measurements of the balloon experiment RUNJOB in a primary energy range of $0.01-0.1$ PeV have shown that the fraction of aligned events agreed with the background expectation [19]. Also the less energetic events recorded during the Concorde flights showed no excess alignment.

A search for such alignment phenomena at accelerators was performed at comparatively low collision energy of 250 GeV in $\pi-$Au interactions. No significant excess of elongated events was found in data of the CERN experiment NA22 [10, 20].

Various theoretical efforts, partly hampered by the limited experimental guidance, were performed to explain alignment by physics mechanisms. It was pointed out in [7] that dynamical features of standard QCD jet production might give rise to observable alignment. In [10, 15] it was emphasized that the observations would indicate aligned particle production in the fragmentation region of the collision rather than in the central region. A connection of alignment to the production of secondaries with high transverse momentum was suggested e.g. in [13, 14]. The appearance of an anti-shadow scattering mode at high collision energies as source of alignment was discussed in [21]. An onset of semi-hard double inelastic diffraction was proposed in [8], where alignment results as projection from the rupture of a quark-gluon string. The existence of a new particle with a long mean free path, produced in a new type of interaction, was also proposed to explain the PAMIR observation [15, 22].

Simulations based on phenomenological models were compared to the PAMIR data in [14, 23]. It was pointed out that alignment features produced, e.g., in the first interaction of the primary cosmic ray in air can be washed out by subsequent interactions during the shower evolution.

While the existence of alignment features is out of doubt, the main questions concerning their nature are: To what extent can such structures observed in the data be related to specific particle production and interaction mechanisms? Are new particles or interaction channels, maybe above a certain collision energy threshold, required to explain the data?

In this work, geometric structures in hadronic shower cores recorded by the KASCADE experiment are investigated. Both, the alignment of hadrons in shower cores and the distance between hadrons are analyzed and compared to detailed Monte Carlo simulations.

The article is organized as follows. In Section II, relevant features of the KASCADE detector and the applied data selection are described. Results on aligned geometric structures are presented in Sec. III, including a detailed study of the background expectation due to random fluctuations. Another observable, characterizing the distance between hadrons, is introduced in Sec. IV and used to analyze KASCADE data. Implications and comparisons to results from other experiments are discussed in Sec. V.

II. MEASUREMENTS

The KASCADE air shower experiment [2] is located at an altitude of 110 m a.s.l. (corresponding to 1020 g cm^{-2} atmospheric depth) at Karlsruhe, Germany. Its 16×20 m^2 hadron calorimeter [3] is well suited to investigate geometric structures in hadronic shower cores. Individual hadrons with energies from 50 GeV up to more than 20 TeV are measured with a spatial resolution of $\simeq 15$ cm. The primary energy covered by KASCADE includes the range of $8-10$ PeV claimed as threshold energy for alignment. A detailed description of the KASCADE detector performance and the standard reconstruction procedures for the array and calorimeter data is given in [2, 3].

For the analysis, data collected by the KASCADE experiment in the period from May 1998 to April 2001 have been used. Primary energy, direction, and core position of air showers with energies >0.5 PeV are determined with the scintillator array data. The energy, position and direction of individual hadrons with energies ≥ 50 GeV are reconstructed from the measurements performed with the hadron calorimeter. The following selection criteria are applied to the data:
(i) The reconstructed primary energy of the air shower ($\Delta E_0/E_0 \simeq 25\%$) is ≥ 1 PeV, and the primary zenith angle is $\leq 30°$ ($\Delta\theta \simeq 1°$).
(ii) The reconstructed shower core location ($\Delta x_c \simeq 1.5$ m) is contained in the active calorimeter area with a minimum distance to the calorimeter boundaries of 3 m.
(iii) At least four hadrons with energies ≥ 100 GeV are reconstructed ($\Delta E_h/E_h \simeq 20\%$).
The effect of the latter condition is small even at lower primary energies, reducing the data set by $\simeq 13\%$.

In total, 4489 events are selected this way. After transformation into the shower plane, the quantities λ_4 and $d_4^{\max}$ (see below) are evaluated for each event. An example of a measured elongated event is given in Fig. 1.

III. ALIGNMENT OF HADRONS

Commonly, the degree of alignment is described by a parameter λ_4 [24] quantifying the angular correlation between the four most-energetic particles (or particle clusters):

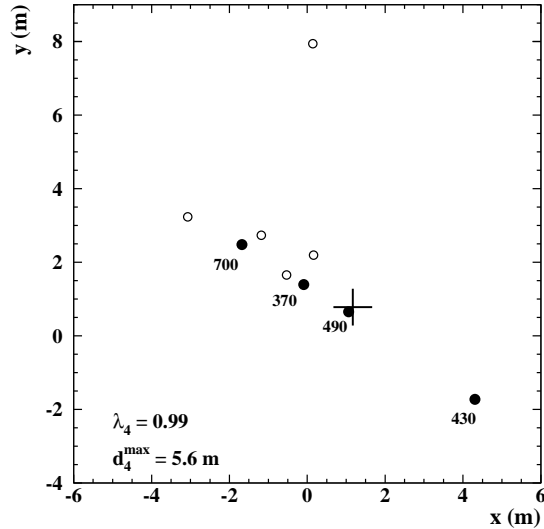$$\lambda_4 = \frac{1}{24} \cdot \sum_{i \neq j \neq k}^{4} \cos 2\varphi_{ij}^k \quad , \qquad (1)$$

FIG. 1: Example of a measured hadronic shower core (hadron positions in the shower plane) with $\lambda_4 = 0.99$ and $d_4^{\max} = 5.6$ m. 9 hadrons with energies above 100 GeV are reconstructed. For the four most energetic hadrons (full symbols), the energies in GeV are given. The shower core position as reconstructed by the scintillator array is marked by a cross. The active calorimeter area exceeds the area plotted.

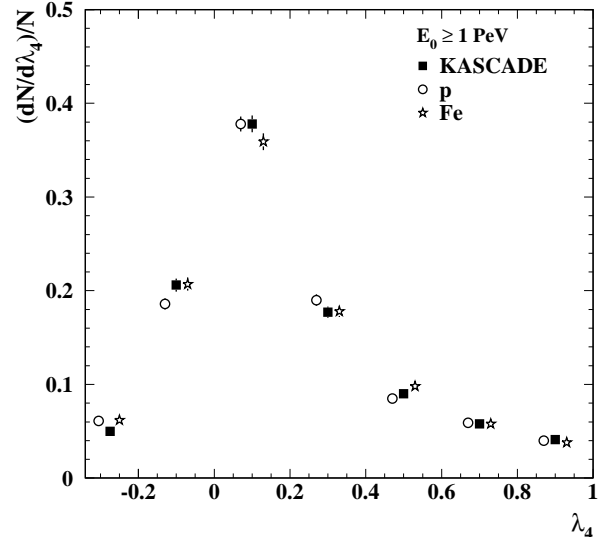FIG. 2: λ_4 distribution measured by KASCADE compared to simulation results for primary proton and iron showers. For clarity, simulation points are slightly displaced horizontally.
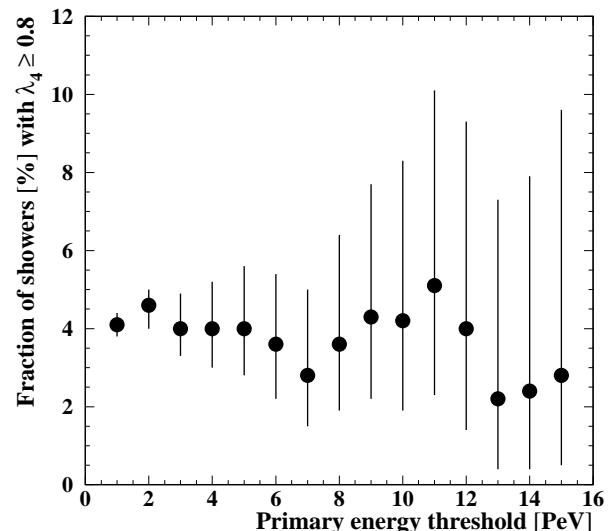

FIG. 3: Fraction of aligned events with $\lambda_4 \geq 0.8$ as measured by KASCADE versus the primary energy threshold.

where φ_{ij}^k denotes the angle between the lines connecting particle k to i and j. Possible values range between $\lambda_4 = -\frac{1}{3}$ (isotropic distribution) and $\lambda_4 = 1$ (perfect alignment). Events are usually termed "aligned" or "elongated" for $\lambda_4 \geq 0.8$.

The measured λ_4 distribution is displayed in Fig. 2. Also shown are the results for primary proton and iron nuclei simulated with the CORSIKA (v6.0) code [27] employing the QGSJET 01 [28] hadronic interaction model. The simulations are performed for a continuous primary energy spectrum with a spectral index -2.7. It has been checked explicitly that adopting other values for the primary energy slope or, e.g., including a *knee* structure does not influence the calculated λ_4 distribution, as will be also clear from the following discussion. The shower simulation is followed by a detailed detector simulation based on GEANT [29]. The same reconstruction algorithms and selection criteria are applied to simulations and data. The simulation statistics is of comparable size to the data statistics for each primary.

Fig. 2 shows that the measured λ_4 distribution and the fraction of aligned events are well reproduced by the standard calculations, without the need of introducing new particles or non-standard interaction features. Moreover, despite the much smaller initial energy per nucleon in case of iron showers, no significant difference between proton and iron induced events is observed. This already indicates a minor sensitivity of the observed parameter λ_4 to hadronic particle production in the first interactions.

The measured fraction of aligned events ($\lambda_4 \geq 0.8$) is plotted in Fig. 3 as a function of the primary energy threshold for selecting showers. Within the statistical uncertainties, no energy dependence of the fraction of elongated events is observed. In particular, no significant increase or threshold behaviour for higher primary energies is found.

In the following, the sensitivity of the observed λ_4 distribution and the fraction of aligned event structures

to specific particle production features is investigated. Events with aligned hadronic structures could be the result of jet production in hadronic interactions during the shower development [7]. The jet pair and the hadrons from projectile fragmentation are naturally aligned in one plane and the expected geometric separation falls in the range measurable with KASCADE. For example, the projected separation from the initial direction of a 10 TeV hadron produced at an altitude of 15 km with a transverse momentum $p_t = 5$ GeV is 7.5 m at KASCADE observation level.

To investigate the correlation between the angular distribution of particles in hadronic interactions and geometric structures, a simulation was carried out in which the azimuth angles of the produced secondary particles are picked at random in the centre-of-mass system of the collision, keeping the transverse and longitudinal momenta unchanged. In this way, any angular correlation of produced particles is eliminated. The results of calculations performed for 5 PeV primary protons are shown in Fig. 4 together with the standard simulations. No significant change of the distribution as a whole or the fraction of aligned events is observed for the modified version (labeled "$\Phi_{\rm random}$") with respect to the original one.

Next, the sensitivity of λ_4 to the transverse momentum p_t of the secondaries is checked. A connection of high-p_t events and alignment was suggested, e.g., in [13, 14]. In the simulation, the p_t of each secondary produced in a hadronic interaction is artificially increased by a factor two (labeled "$2 \cdot p_t$" in Fig. 4), keeping the original angular correlations unchanged. Such an increase is not realistic, but used here to study the sensitivity. The overall shape of the λ_4 distribution is affected very little. No significant change of the fraction of aligned events can be noted.

This insensitivity to modifications of the hadronic particle production suggests that the measured λ_4 distribution is mostly due to a random distribution of the hadron azimuth angles. Thus, a simplified simulation is performed by artificially generating sets of four hadron positions in the shower plane. The azimuth angles of the hadrons are chosen randomly with respect to the shower core. The lateral distances of the hadrons are sampled according to the measured lateral distribution of the four most energetic hadrons. The KASCADE data are indeed reproduced, see Fig. 5.

The sensitivity of the λ_4 distribution to the shape of the lateral distribution of the observed particles is checked with the simplified simulation by varying the assumed lateral shape, keeping the choice of hadron azimuth angles at random. It should be noted that λ_4 as an observable, being determined from the event topology, does not depend on the absolute length scale of the assumed lateral distribution, but only on its shape. As can be seen in Fig. 6, even choices of functional forms that are unrealistic for air shower lateral distribution such as adopting a particle density that is constant for any distance from the core, result only in modest changes of the
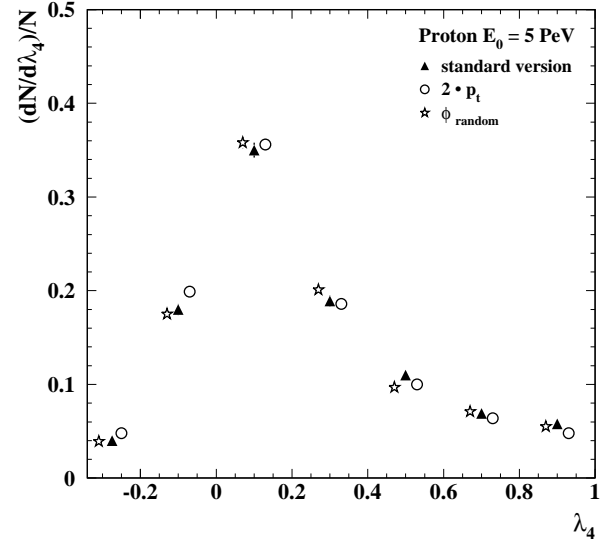

FIG. 4: λ_4 distributions for proton showers of 5 PeV primary energy without modification of the hadronic particle production ("standard version"), with randomly chosen azimuth angles of secondary hadrons ("$\Phi_{\rm random}$"), and with transverse momenta of secondary hadrons increased by a factor two ("$2 \cdot p_t$"). Simulation points obtained after the modifications are slightly displaced horizontally.
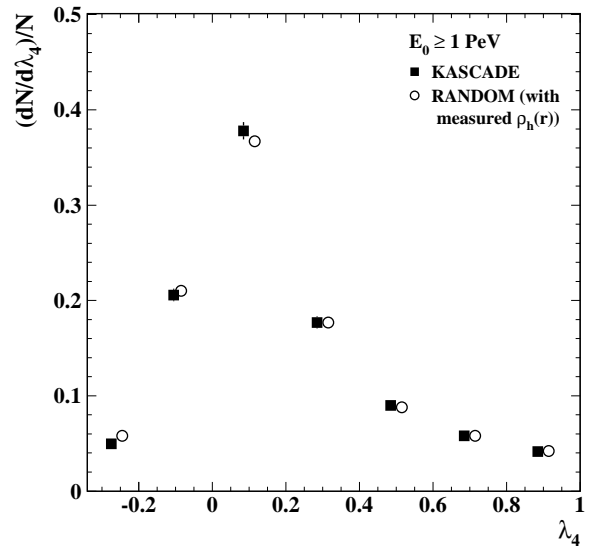

FIG. 5: λ_4 distributions: KASCADE data and results from a simplified simulation of event topologies, in which the azimuth angles were chosen randomly with respect to the shower core, and the distances according to the measured hadron lateral distribution (see text). Simulation points are slightly displaced horizontally.
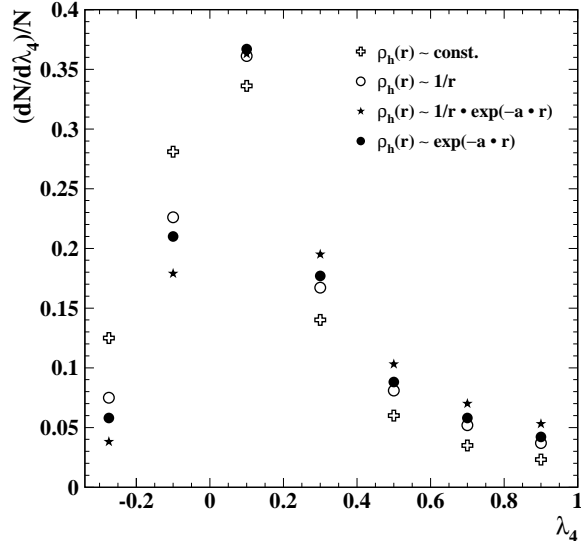
FIG. 6: λ_4 distributions obtained by a simplified simulation of event topologies (see text or caption of Fig. 5) for different hypothetical shapes of the lateral distribution as indicated.
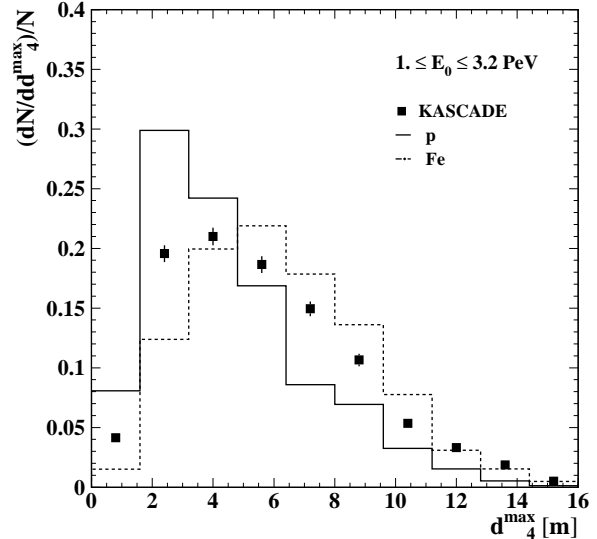

FIG. 7: $d_4^{\max}$ distribution measured by KASCADE compared to simulation results for primary proton and iron showers for primary energies of 1-3.2 PeV.

λ_4 distribution. In general, a flatter lateral distribution tends to decrease the fraction of aligned events generated in the random sample. However, the sensitivity of λ_4 to different lateral shapes is minor. It seems hardly possible for an air shower experiment to observe differences between λ_4 distributions that are due to different lateral distributions of the measured particles only.

Other parameters describing geometric structures similar to λ_4 have been checked for sensitivity to primary mass or hadronic interaction characteristics [30]. For instance, all hadrons ≥ 100 GeV instead of the four most energetic ones are considered to calculate a generalized quantity λ_n. Also, weight factors for the hadrons are introduced to additionally take their reconstructed energy into account. No significant sensitivity to hadronic particle production properties of these λ-related quantities is found, either.

IV. DISTANCE BETWEEN HADRONS

Hadronic shower observables with sensitivity to interaction features have for instance been discussed in [4, 6]. A specific, further observable that is based on the four most energetic hadrons in each event as is λ_4, is given by the maximum distance, $d_4^{\max}$, between one of the four considered hadrons to the geometric centre of the other three [26]. Since this quantity is intimately connected to the hadron lateral distribution, a sensitivity both to hadronic interaction features such as the transverse momentum of secondary hadrons and to the primary particle type can be expected.

The $d_4^{\max}$ distribution measured by KASCADE at en-

ergies 1-3.2 PeV is compared to simulation results for primary proton and iron showers in Fig. 7. The comparison is restricted to energies below the *knee* due to the increasing uncertainty of primary flux spectra and composition at higher energy. The $d_4^{\max}$ distribution for primary protons is peaked at smaller values compared to the predictions for iron-initiated events, reflecting a steeper hadron lateral distribution in case of air showers initiated by proton primaries.

The KASCADE data are mostly bracketed by the primary proton and iron expectations. This seems reasonable, as for these primary energies a mixed composition is favoured from extrapolations of direct cosmic-ray measurements, from other air shower experiments and in particular from the analysis of independent KASCADE observables such as the electron and muon shower sizes [31]. Only at largest $d_4^{\max}$ values, a slight underestimation shows up in the predictions that may indicate shortcomings in the modelling of hadron interactions.

In the next step, as before, the p_t of secondary hadrons is artificially modified in the simulations. The results are compared to KASCADE data in Fig. 8. Assuming transverse momenta of secondary hadrons produced in high-energy interactions twice as large as in standard simulations (upper panel in Fig. 8), the distributions both for proton and iron primaries are significantly shifted to larger $d_4^{\max}$ values. In this scenario, the simulations are hardly able to provide a satisfactory description of the $d_4^{\max}$ data. For any assumption on the primary composition between proton and iron nuclei, and in particular for a mixed composition as favoured by other measurements, events with small values of $d_4^{\max}$ observed in hadronic shower cores are not adequately reproduced by simula-
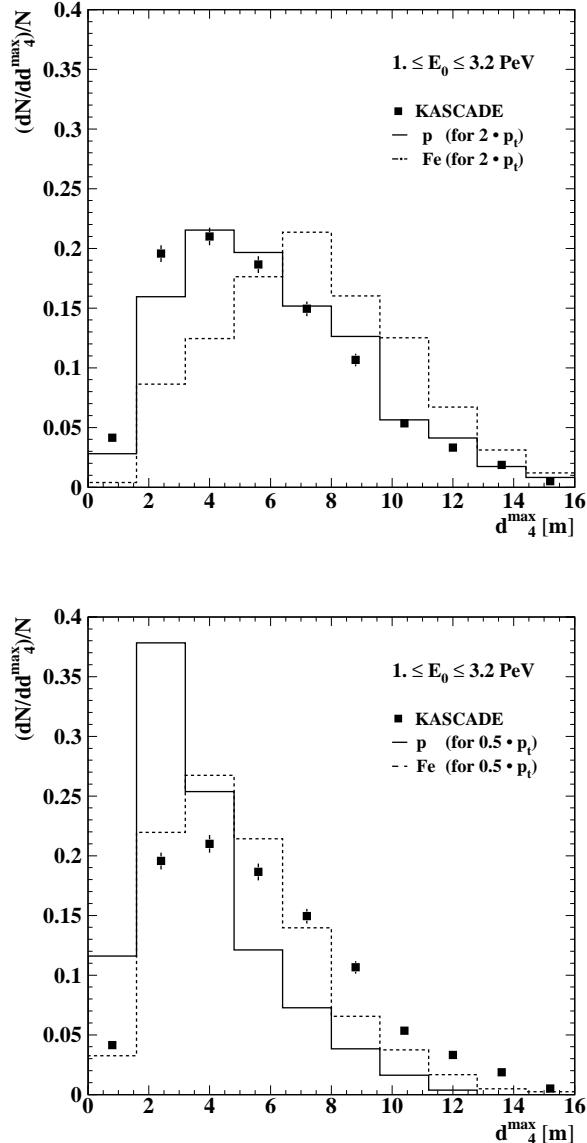
FIG. 8: $d_4^{\max}$ distribution measured by KASCADE (see Fig. 7) compared to simulation results for primary proton and iron showers with modified transverse momentum of secondary hadrons. The transverse momenta were artificially increased (upper panel, "$2 \cdot p_t$") and reduced (lower panel, "$0.5 \cdot p_t$") by a factor two.

tions with doubled p_t. The same conclusion holds when artificially reducing the p_t of secondary hadrons by a factor two (lower panel in Fig. 8). In this case, the simulations fail to describe the events observed with large values of $d_4^{\max}$. Therefore, hypothetical transverse momenta in high-energy secondary hadron production that differ by a factor two or more from the standard assumptions are disfavoured by the KASCADE data.

Another application of the $d_4^{\max}$ parameter is related to investigating the primary cosmic-ray composition by

means of air shower simulations. Due to the sensitivity to the primary particle type, quantities such as $d_4^{\max}$ can be used to check the internal consistency of hadronic interaction models.

V. DISCUSSION

The results of the KASCADE data analysis concerning the λ_4 parameter can be summarized as follows. The measured λ_4 distribution and the fraction of aligned events of high-energy hadrons are well reproduced by the simulations. Moreover, the data follow the expectations from randomly distributed hadron azimuth angles. No significant dependence on the primary energy was observed. Within the statistical uncertainty, no correlation between λ_4 and hadronic interaction features such as jet production was found.

These results are not necessarily in contradiction to possible alignment excesses in other shower observables, at different observation levels, or in a different primary energy range. However, the absence of an alignment excess in the present analysis might be used to constrain attempted alignment explanations.

The KASCADE data can be compared to the λ_4 distribution measured by the PAMIR detector. PAMIR [9, 10] is an emulsion chamber experiment located at an altitude of 4360 m a.s.l. (corresponding to 600 g cm^{-2} atmospheric depth), measuring air shower hadrons and photons with a particle energy threshold of a few TeV.

In Fig. 9, the λ_4 distributions obtained from KASCADE and PAMIR data [11, 15] are compared for two different primary energies. In the energy range of a few PeV (upper panel of the Figure), i.e. below the threshold energy of the alignment excess claimed from PAMIR data, both distributions and the fraction of aligned events agree well to each other. This is a quite significant result, since in the PAMIR experiment, compared to KASCADE, a completely different detection technique is applied, the mass overburden is considerably smaller ($\Delta X_v \simeq 420$ g cm^{-2}), and the energy threshold of the registered shower particles is higher by more than an order of magnitude. A possible interpretation of this concordance is that both λ_4 distributions are generated mostly from a random distribution. Also possible differences in the lateral distributions of the particles measured by KASCADE and PAMIR seem too small to significantly affect the λ_4 distributions.

This interpretation is supported by comparing the fraction of aligned events measured by KASCADE $F(\lambda_4 \geq 0.8) \simeq (4\pm1)\%$ with the values derived from RUNJOB of $(3\pm1)\%$ [19] and from NA22 data ($\simeq 6\%$) [10, 20]. Each result was found to agree to the respective background fluctuation, and despite the completely different measurement conditions, the fractions of aligned events are comparable to each other.

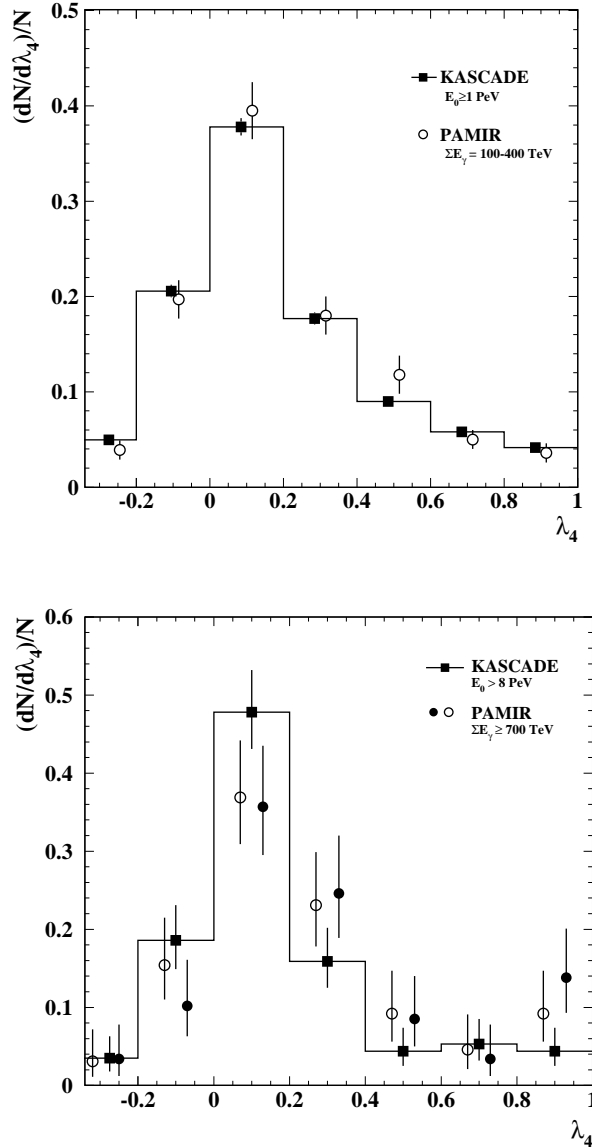For a higher primary energy range, based on λ_4 distributions obtained from PAMIR data such as shown in

Fig. 9 (lower panel), an alignment excess with a threshold energy of $8-10$ PeV was deduced [11, 15]. Displayed in the Figure are two distributions obtained with different reconstruction methods from the same PAMIR data set. Included in the graph are the KASCADE results for primary energies above 8 PeV. Despite the completely different observation conditions, the distributions measured by both experiments agree well to each other. The fraction of events with $\lambda_4 \geq 0.8$ is larger in the PAMIR data compared to KASCADE. However, the statistical significance for the fraction of aligned events to differ between the two experiments is small, amounting to $\simeq 1.5$ standard deviations only. Thus, also in this primary energy range the lack of significant differences between the λ_4 distributions, including the fraction of aligned events, suggests a random component as a dominant source of the λ_4 values observed by both, PAMIR and KASCADE.

The quantity d_4^{max}, describing distances between the hadrons as measured by the KASCADE calorimeter, is sensitive to the transverse momenta in secondary hadron production and to the primary particle type. Transverse momenta in high-energy hadron interactions differing by a factor two or more from the standard values are disfavoured by the measurements.

FIG. 9: λ_4 distributions: KASCADE and PAMIR [11, 15] data. In the lower panel, the highest primary energies are selected. The two distributions displayed for PAMIR in the lower panel refer to different reconstructions from the same PAMIR data set [11, 15]. PAMIR data are slightly displaced horizontally.

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